

Differential chemical abundance analysis of a 47 Tuc AGB star with respect to Arcturus

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ABSTRACT

This study resolves a discrepancy in the abundance of Zr in the 47 Tucanæ asymptotic giant branch star Lee 2525. This star was observed using the echelle spectrograph on the 2.3 m telescope at Siding Spring Observatory. The analysis was undertaken by calibrating Lee 2525 with respect to the standard giant star Arcturus. This work emphasises the importance of using a standard star with stellar parameters comparable to the star under analysis rather than a calibration with respect to the Sun (Koch & McWilliam 2008). Systematic errors in the analysis process are then minimised due to the similarity in atmospheric structure between the standard and programme stars. The abundances derived for Lee 2525 were found to be in general agreement with the Brown & Wallerstein (1992) values except for Zr. In this study Zr has a similar enhancement ($[Zr/Fe] = +0.51$ dex) to another light s -process element, Y ($[Y/Fe] = +0.53$ dex), which reflects current theory regarding the enrichment of s -process elements by nuclear processes within AGB stars (Busso et al. 2001). This is contrary to the results of Brown & Wallerstein (1992) where Zr was under-abundant ($[Zr/Fe] = -0.51$ dex) and Y was over-abundant ($[Y/Fe] = +0.50$ dex) with respect to Fe.

Key words: globular clusters: individual: 47 Tuc, nucleosynthesis, stars: abundances, stars: individual: Arcturus.

1 INTRODUCTION

The globular cluster 47 Tucanæ (47 Tuc) has proven to be a rich source of study with regards to the structure and evolution of stars and stellar systems. Chemical abundance studies have indicated the presence of light element abundance anomalies between the stars at all stages of stellar evolution. Recent advances in telescope and instrument sensitivity are providing observation of larger samples of stars within clusters at higher resolution enabling a more detailed investigation of the exact nature of the abundance anomalies. A significant advance has been the greater number of abundances derived for the elements heavier than iron. In particular the light and heavy s -process elements which provide signatures of key stages in stellar evolution.

A well studied phenomenon in 47 Tuc is the CN weak, CN strong bimodality which is seen at all stages of stellar evolution in 47 Tuc (Cannon et al. 1998). Internal mixing cannot solely explain this anomaly and some primordial or pollution mechanism is required to account for it being observed on the main sequence and giant

branches (Cannon et al. 1998; Briley et al. 2004). Also observed in 47 Tuc is a correlation of Na to CN strength (Cottrell & Da Costa 1981). However there has been no observational evidence of a correlation of either Mg or Al with CN or Na as can be observed in more metal poor clusters though Na has been observed to anti-correlate with O in 47 Tuc (Carretta et al. 2004). As these anomalies have been observed in giants and dwarfs it is theorised they are most likely due to primordial scenarios rather than solely due to internal mixing in globular cluster stars. For a complete summary of these anomalies in 47 Tuc and other globular clusters refer to the recent review paper, Gratton et al. (2004).

Recent stellar studies have investigated the abundances of elements heavier than iron and have shown an enhancement in s -process elements in 47 Tuc. Brown & Wallerstein (1992) analysed four giant stars in 47 Tuc for their light and heavy element abundances, determining for the s -process elements an average enhancement in Y ($[Y/Fe] = +0.48 \pm 0.11$ dex) but a depletion in Zr ($[Zr/Fe] = -0.22 \pm 0.05$ dex). Alves-Brito et al. (2005) analysed a sample of five 47 Tuc giant stars and found Zr to also be depleted ($[Zr/Fe] = -0.17 \pm 0.12$ dex) though did not obtain abundances for Y. However Wylie et al. (2006) found an overall enhance-

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ment in *s*-process elements, including Zr ($[Zr/Fe] = +0.65 \pm 0.16$ dex) and Y ($[Y/Fe] = +0.64 \pm 0.20$ dex), in seven giant branch stars in 47 Tuc. In a study of 3 turn-off and 8 subgiants in 47 Tuc James et al. (2004) found enhancements in Sr and Ba, but Y was depleted for the subgiants ($[Y/Fe] = -0.11 \pm 0.10$ dex) and slightly enhanced for the turnoff stars ($[Y/Fe] = +0.06 \pm 0.010$ dex). While the results are consistent within each study the variation between studies are contradictory to the expected homogeneous distribution of heavy elements in globular cluster stars.

The primary source for *s*-process element production are nuclear reactions that occur during the asymptotic giant branch (AGB) stage of stellar evolution (Busso et al. 2001). AGB stars of mass greater than $1.5 M_{\odot}$ undergo third dredge up (TDU) during which seed nuclei (Fe) are exposed to neutron fluxes. This builds up heavier and heavier nuclei resulting in the observed enhancements in *s*-process element abundances in thermally pulsing AGB stars. Due to small reaction cross-sections, elements are first built up in the light *s*-process peak ($ls = \langle Sr, Y, Zr \rangle$) then in the heavy *s*-process peak ($hs = \langle Ba, La, Nd \rangle$) (Busso et al. 2001). The ratios of $[ls/Fe]$, $[hs/Fe]$ and $[hs/ls]$ are used as indicators of the degree of *s*-process enhancement and neutron flux. A depletion in Zr coinciding with an enrichment in Y, as determined in Brown & Wallerstein (1992), is not a likely result in a scenario of enrichment due to AGB stars. There are other potential sources for the *s*-process elements. The AGB source is referred to as the ‘main’ *s*-process. The ‘weak’ *s*-process occurs during He-core burning in massive stars and can enhance light *s*-process elements such as Sr and Y (Arlandini et al. 1999). The *r*-process, rapid neutron exposures typically in supernovae, can also contribute to the abundances of *s*-process elements. The contributions from these different sources can be disentangled by comparing heavy elements whose abundances are mainly *s*-process (such as Y and Zr) to those who are mainly *r*-process, such as Eu, to those who have contributions in different ratios from these sources (Travaglio et al. 2004).

While there are these different potential sources for each of the *s*-process elements, including contributions from the *r*-process, for the most part it is argued that the abundance of a heavy element is homogeneous within a cluster. The differing results for Zr (and Y) need to be resolved in order to pursue the connections between heavy and light element abundances. These connections provide clues as to the nature of primordial and mixing scenarios that could lead to chemical abundance distributions that are seen in globular cluster stars.

2 OBSERVATIONS AND PREVIOUS WORK

In November 2007 the 47 Tuc giant branch star Lee 2525 was observed on the 2.3 m telescope at the Siding Spring Observatory by K.C. Freeman and E.C. Wylie-de Boer. It was observed using the échelle spectrograph, obtaining wavelengths from 4500 Å to 6500 Å. The spectrum had a resolution of $R \sim 20,000$ with a signal to noise per resolution element of ~ 35 . The spectrum was reduced in IRAF and the normalised spectrum underwent the same equivalent width analysis as the calibration star Arcturus (see Section 3.1). Lee 2525 had been observed previously in

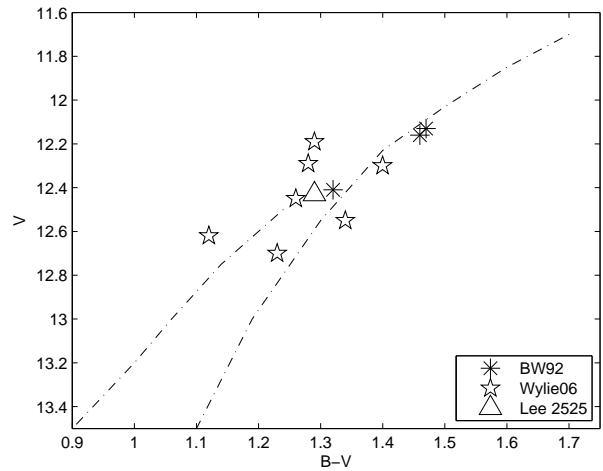


Figure 1. Colour-magnitude diagram of 47 Tuc showing the placement of the giant stars observed in Brown & Wallerstein (1992) and Wylie et al. (2006). The fiducial lines indicating the RGB and AGB branches of 47 Tuc are from Hesser et al. (1987).

Brown & Wallerstein (1992), along with four other 47 Tuc giant branch stars. In Wylie et al. (2006) these stars were compared with seven more giant stars in 47 Tuc.

Figure 1 shows the placement of the stars in both studies on the colour-magnitude diagram of 47 Tuc. Lee 2525 is also indicated on the diagram and all of the stars fall on the red giant branch (RGB) or AGB as indicated by the fiducial lines (Hesser et al. 1987).

Lee 2525 has been studied in a number of papers. As a bright giant it was initially observed under this designation in Lee (1977). Subsequently it was studied in Norris & Freeman (1979) where it was determined to be a CN weak AGB star. It has also been part of a mass loss rate study for giant stars in 47 Tuc where it was determined to have no infrared excess (Ramdani & Jorissen 2001). Lee 2525 was analysed in Brown & Wallerstein (1992) as the CN weak star in a CN weak-CN strong pair. Its counterpart was Lee 1513.

Worley et al. (2008) observed Lee 2525 as part of a study into the feasibility of medium-resolution surveys of globular cluster stars to determine their *s*-process elemental abundances using the Robert Stobie Spectrograph (RSS) on the Southern African Large Telescope (SALT). For Lee 2525 in particular there was an indication of an enhancement in Zr, although this lay within the uncertainties of the model abundance. The resolution of the spectra in this study was determined to be too low ($R \sim 5,000$) to determine absolute *s*-process element abundances, although upper limits of 0.5 dex may be possible in future higher resolution observations with RSS.

The average heavy elemental abundances for the stellar samples reported in Brown & Wallerstein (1992) and Wylie et al. (2006) are listed in Table 1.

The sample in Wylie et al. (2006) show a general enhancement of the *s*-process elemental abundances across the sample, with the average enhancement for Zr being $[Zr/Fe] = +0.65$ dex. A similar abundance enhancement was found for several *s*-process elements in Brown & Wallerstein

Table 1. Comparison of the mean heavy elemental abundances from samples of AGB and RGB stars analysed in Brown & Wallerstein (1992) (BW92) and Wylie et al. (2006) (W06).

	BW92	Wylie06
No. Stars	4	7
$\langle[\text{Fe}/\text{H}]\rangle$	-0.81	-0.63
$\langle[\text{Y}/\text{Fe}]\rangle$	+0.48	+0.64
$\langle[\text{Zr}/\text{Fe}]\rangle$	-0.22	+0.65
$\langle[\text{La}/\text{Fe}]\rangle$	+0.18	+0.31
$\langle[\text{Eu}/\text{Fe}]\rangle$	+0.25	+0.15

(1992), but Zr was found to be depleted with an average abundance of $[\text{Zr}/\text{Fe}] = -0.22$ dex. Y was enhanced in both studies as was La and Eu.

The goal of this analysis of Lee 2525 is to link these two studies in an effort to consolidate the reported abundances of heavy elements in 47 Tuc giant branch stars.

3 SPECTRAL DERIVATION OF STELLAR PARAMETERS

For sufficiently high resolution observations the determination of the spectral parameters of a star can be carried out using a curve of growth analysis. A curve of growth analysis allows the simultaneous determination of the effective temperature (T_{eff}), surface gravity ($\log g$), metallicity ($[\text{Fe}/\text{H}]$) and microturbulence (ξ) of a star. For both Arcturus and Lee 2525, the normalised spectrum was measured for the equivalent widths of selected Fe I and Fe II lines. Using MOOG (Snedden 1973), these equivalent widths were used to determine the best fit stellar model by balancing the derived abundances ($\log(\epsilon)$) with excitation potential (χ) to find T_{eff} , with reduced equivalent width ($\log(\frac{W}{\lambda})$) to find ξ , and with wavelength λ . The derived $\log(\epsilon)$ values for Fe I and Fe II were required to balance in order to find the correct $\log g$.

3.1 Arcturus calibration

Deriving abundances relative to the Sun may not be appropriate for giant stars as so many features present in giant stars are not present in the solar spectrum. Deriving the abundances relative to Arcturus, a giant star of similar metallicity to 47 Tuc, is a more appropriate choice as the similarities in atmospheric structure will cancel out any systematic errors (Koch & McWilliam 2008).

The equivalent widths of spectral lines in Arcturus were measured in order to calibrate the analysis process used in this study. The equivalent widths of all possible Fe I and Fe II lines were measured from the high resolution atlas of Arcturus (Hinkle & Wallace 2005).

Lines with equivalent width greater than 180mÅ were rejected as they are saturated and also less accurate due to the assumption of a gaussian profile fit in the determination of equivalent width. The stellar parameters for Arcturus were derived using the MOOG curve of growth analysis *abfind* function. The latest available published $\log gf$ values from VALD were used for this Fe line list (Kupka et al. 2000).

MOOG derives abundances based on local thermodynamic equilibrium calculations and assumes the model has a plane parallel geometry for the structure of the stellar atmosphere. Spherical geometry stellar models are more representative of the atmospheric structure of giant stars and can be used in MOOG with the above codicil in mind. The stellar parameters for Arcturus were derived using a MARCS spherical geometry model (Gustafsson et al. 2008) and an Kurucz/Atlas9 plane parallel model (Kurucz 1979; Kurucz 1995). Table 2 compares the Arcturus stellar parameters derived here using plane parallel and spherical geometry with the values obtained in Fulbright et al. (2006).

The best fitting stellar parameters for both the spherical and plane parallel geometry models are in close agreement with each other and with that derived in Fulbright et al. (2006).

The determination of the remaining element abundances proceeded by two methods. For the light elements (O through Zn), which have sufficiently isolated lines, equivalent widths were measured and used with the best fit model and *abfind* in MOOG to derive abundances. For the weaker lines and those of the heavy elements (Y to Eu) in more crowded spectral regions, abundances were derived by comparing synthesised and observed spectra. The spectrum synthesis line lists in key *s*-process regions were calibrated to the observed Arcturus spectrum using *synth* in MOOG. The $\log gf$ values for the key *s*-process lines were taken from the latest published laboratory values: Lawler et al. (2001), Biemont et al. (1981), Den Hartog et al. (2003), Hannaford et al. (1982).

An abundance analysis of the light elements in Arcturus was carried out in Fulbright et al. (2007) and the values derived here are compared with that study in Table 2. There is very little change between the light element abundances derived using the spherical model compared with the plane parallel model. Comparing the spherical model to the Fulbright et al. (2007) values there is reasonable agreement (≤ 0.1 dex) between the two sets of abundances. Given the close agreement between the derived abundances of the spherical and plane parallel models, and the good agreement with Fulbright et al. (2007), the spherical model was selected as the stellar model for Arcturus in this analysis.

The derived Arcturus abundances for the light and heavy species, and uncertainties associated with changes in T_{eff} , $\log g$ and ξ , are listed in full in Table 3.

The uncertainties associated with changes in T_{eff} , $\log g$ and ξ are sufficiently greater than the abundance differences between the spherical and plane parallel models that the stellar parameter selection can be considered to introduce a more significant error than the geometry upon which the model is based. The parameter uncertainties can account for differences in the light element abundances between this study and Fulbright et al. (2007), except for the Al I which is due to different line selection between the studies. With regard to the heavy elements the neutral species are most affected by changes in T_{eff} , while the ionised species are more affected by changes in $\log g$. The Ba II abundance varies greatly with all three parameters which can be explained due to it being derived from two strong lines that are sensitive to variations with ξ and T_{eff} , and, as an ionised species, a large variation with $\log g$.

Table 2. Comparison of the derived light element abundances for Arcturus from Fulbright et al. (2007) and this study. In this study two stellar models were considered in order to compare the results from MOOG of spherical versus plane parallel geometry input models.

Geometry	Fulbright06				This study				
	Plane Parallel				Spherical	Plane Parallel			
T_{eff}	4290K				4300K	4270K			
$\log g$	1.55				1.6	1.7			
[Fe/H]	-0.5dex				-0.6dex	-0.60dex			
ξ	1.67 km s^{-1}				1.50 km s^{-1}	1.50 km s^{-1}			
X	[X/Fe]	σ	N		[X/Fe]	σ	[X/Fe]	σ	N
O	0.48	-	1		0.57	0.02	0.56	0.03	2
Na	0.09	-	1		0.15	0.04	0.14	0.04	2
Mg	0.39	0.06	5		0.34	0.15	0.32	0.15	8
Al	0.38	0.03	3		0.25	0.07	0.24	0.07	4
Si	0.35	0.05	15		0.24	0.14	0.21	0.14	10
Ca	0.21	0.01	2		0.19	0.06	0.19	0.06	12
Ti	0.26	0.04	24		0.34	0.15	0.34	0.11	29
Fe	-	-	-		[X/H]	σ	[X/H]	σ	N
					-0.59	0.12	-0.62	0.11	40

Table 3. Derived element abundances for Arcturus with uncertainties in [Fe/H] and [X/Fe] associated with changes in T_{eff} , $\log g$ and ξ using spherical geometry stellar models.

Species						Δ [X/H]
X	N	[X/H]	σ	ΔT_{eff} +100K	$\Delta \log g$ +0.5	$\Delta \xi$ +0.5km s ⁻¹
Fe I	29	-0.61	0.12	0.06	0.13	-0.29
Fe II	11	-0.56	0.05	-0.20	0.21	-0.13
X	N	[X/Fe]	σ	Δ [X/Fe]		
O I	2	0.57	0.02	-0.01	0.20	-0.02
Na I	2	0.15	0.04	0.09	0.01	-0.10
Mg I	8	0.34	0.15	0.01	0.03	-0.04
Al I	4	0.25	0.07	0.07	0.01	-0.07
Si I	10	0.24	0.14	-0.06	0.13	-0.06
Ca I	12	0.19	0.06	0.12	-0.03	-0.26
Sc II	2	0.24	0.01	-0.02	0.22	-0.18
Ti I	24	0.35	0.12	0.17	0.04	-0.15
Ti II	5	0.33	0.10	-0.04	0.22	-0.15
Zn I	2	-0.04	0.09	-0.07	0.14	-0.26
Y I	3	0.07	0.24	0.21	0.03	-0.07
Y II	5	0.12	0.11	0.02	0.22	-0.04
Zr I	7	0.01	0.07	0.13	0.07	0.00
Zr II	3	0.12	0.10	-0.01	0.24	-0.01
Ba II	2	-0.19	0.08	0.27	0.26	-0.16
La II	6	0.04	0.08	0.04	0.19	-0.02
Nd II	4	0.10	0.07	0.03	0.17	-0.09
Eu II	2	0.36	0.04	-0.02	0.23	-0.01

3.2 Lee 2525 stellar model

As part of an ongoing programme of research into the nature of *s*-process elemental abundances in globular cluster giant stars the Zr discrepancy between the studies of Brown & Wallerstein (1992) and Wylie et al. (2006) needed

to be addressed. This motivated the high resolution observation and analysis of Lee 2525. The stellar parameters derived for Lee 2525 in Brown & Wallerstein (1992) were $T_{eff} = 4225 \text{ K}$, $\log g = 1.3$, [Fe/H] = -0.82 dex and $\xi = 2.0 \text{ km s}^{-1}$.

Equivalent widths from the Lee 2525 spectrum were measured for each of the Fe I and Fe II lines that were used in the analysis of Arcturus. Due to the much lower resolution and SNR of this spectrum compared with the Arcturus atlas, careful selection of the best fitted lines was made with which to determine the stellar parameters for Lee 2525. This reduced the list from 40 to 22 lines in total. Local normalisation about each Fe line in the stellar spectra was necessary to ensure the correct location of the continuum. Fulbright et al. (2006) defined continuum regions that were clear of molecular bands about each of the Fe lines in Arcturus. These regions were used in the local normalisation about each of the Fe lines measured in Lee 2525. An example of the normalisation and measurement of equivalent width process for the Fe I line at 6127.906 \AA in the Lee 2525 stellar spectrum is shown in Figure 2.

The normalisation was made by finding the mean intensity and wavelength of each of the Fe lines' two continuum regions. The mean was calculated iteratively, discarding points that lay outside 2σ of the mean and then recalculating until less than 5% of the remaining points lay outside the 2σ limit. A linear relation between the two mean points was then divided out from the spectrum resulting in the required normalisation. If only one continuum region was available, the mean intensity of that region was divided out of the spectrum to effect the normalisation. Given the low SNR of the spectrum, this continuum placement was considered to be too high (see dashed line profile in Figure 2). A further downward vertical shift of 0.03 (as the noise per pixel was equivalent to $\pm 3\%$ of the signal) was applied in order to take

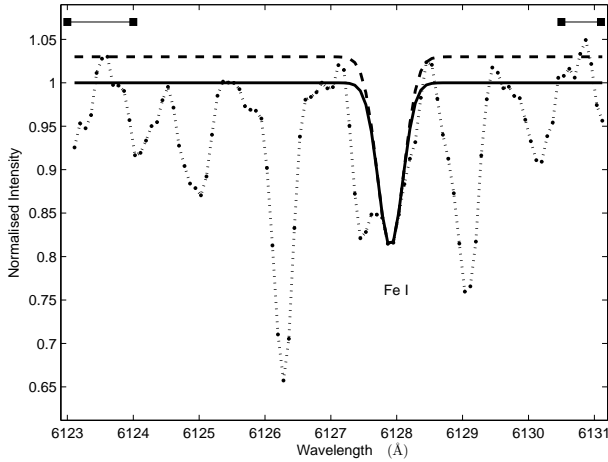


Figure 2. Fe I line at 6127.906 Å in the Lee 2525 stellar spectrum. The dotted line is the observed spectrum. The black square line segments are the continuum regions used to normalise the spectrum locally about the line. The solid line is the line profile used to determine the equivalent width for this line where the continuum has been placed so as to account for the low SNR of the spectrum. The dashed line is the line profile where the SNR has not been taken into account.

account of the high degree of noise in the spectrum (solid line profile in Figure 2).

Figure 2 clearly shows that a much larger equivalent width would be measured if the noise was not taken into account. For the Fe I line at 6127.906 Å the equivalent width for which the SNR was accounted for in the continuum placement was measured to be 98.8 mÅ. If the SNR was not accounted for in the continuum placement the equivalent width was measured to be 119.4 mÅ. Similar measurements were carried out for each of the Fe lines. This shows that the placement of the continuum, and consequently the measurement of the equivalent widths is a key source of uncertainty in this analysis. The Fe and atomic lines were carefully inspected and consistently measured by the above procedure in order to minimise this uncertainty.

In this study the Brown & Wallerstein (1992) values of T_{eff} and $\log g$ (4225 K and 1.3 respectively) for Lee 2525 were used as the starting point for determining the spectroscopic stellar model. An exploration in stellar parameter space was carried out in order to determine the best fit model. Table 4 lists the stellar parameters and resulting [Fe I, Fe II/H]¹ values for each model permutation.

Figure 3 compares [Fe/H] against χ for Arcturus, the Brown & Wallerstein (1992) model for Lee 2525 and two prospective models for Lee 2525 derived in this study.

In Figure 3a the small spread in values is obvious for Arcturus due to the much greater resolution and high signal to noise of that spectrum. The Arcturus models at $\xi = 2.0 \text{ kms}^{-1}$ and $\xi = 1.5 \text{ kms}^{-1}$ are compared showing that Arcturus clearly falls in the $\xi = 1.5 \text{ kms}^{-1}$ regime, illustrated by the smaller spread in [Fe/H] values (see Table 4).

The stellar model matching the Brown & Wallerstein

(1992) parameters for Lee 2525 (Figure 3b) show good agreement between the derived Fe I and Fe II abundances in the $\xi = 2.0 \text{ kms}^{-1}$ regime. For the $\xi = 1.5 \text{ kms}^{-1}$ regime the [Fe I, Fe II/H] values are out of equilibrium and the [Fe I/H] disagrees with the model [Fe/H] by ~ 0.2 dex (see Table 4). Figure 3c uses a model for Lee 2525 at [Fe/H] = -0.65 dex which returns [Fe/H] = -0.62 dex for $\xi = 1.5 \text{ kms}^{-1}$. The spread in values are reasonable and tighter than the spread in the $\xi = 2.0 \text{ kms}^{-1}$ regime.

Ultimately the best fit model, shown in Figure 3d resides closer to the $\xi = 2.0 \text{ kms}^{-1}$ regime at $\xi = 1.8 \text{ kms}^{-1}$ where the spread in values is reasonable for both the Fe I and Fe II abundances. Hence the best fit model for Lee 2525 derived in this study returned values of $T_{eff} = 4225 \text{ K}$, $\log g = 1.2$, [Fe/H] = -0.70 dex and $\xi = 1.8 \text{ kms}^{-1}$ (see Table 4), which are in reasonable agreement with the values derived in Brown & Wallerstein (1992).

The Fe abundances derived from the Fe I and Fe II lines using the best fit stellar atmosphere model were -0.72 ± 0.16 dex and -0.74 ± 0.08 dex respectively. These values were derived from the equivalent widths measured such that the continuum placement took account of the low SNR of the Lee 2525 spectrum, as outlined above. Using the best fit Lee 2525 stellar model, Fe abundances were re-derived from the equivalent widths measured without taking the SNR into account. The respective values were determined to be [Fe I/H] -0.37 ± 0.17 dex and -0.29 ± 0.10 dex. These values are considerably more metal-rich and reflect an increase in derived abundance of ~ 0.3 dex from the Fe I lines and ~ 0.4 dex from the Fe II lines due to the increased equivalent width values. The weaker Fe II lines show a larger change as the increase in equivalent width is proportionally greater than for the strong Fe I lines. These values reflect the maximum possible uncertainty introduced by the spectrum's low SNR. However, the equivalent width measurements and abundance analysis were carried out in a consistent manner with careful inspection of the lines to ensure the best placement of the continuum in order to minimise this uncertainty.

The best fit stellar model for this study returned an average [Fe/H] of -0.73 dex which is slightly more metal-rich than the Brown & Wallerstein (1992) value of -0.82 dex. Comparing these values to previous studies of RGB and AGB stars in 47 Tuc, both are more metal-poor than Alves-Brito et al. (2005), which found an average [Fe/H] of -0.68 dex, Carretta et al. (2004) ([Fe/H] = -0.67 dex) and Wylie et al. (2006) ([Fe/H] = -0.60 dex). However, a more recent paper, Koch & McWilliam (2008), derived an [Fe/H] of -0.76 dex for 47 Tuc with their stars having a range of values from -0.82 dex to -0.72 dex. This is significantly more metal-poor than previous studies and in better agreement with the derived metallicities of Lee 2525 found in this study and Brown & Wallerstein (1992).

4 ELEMENT ABUNDANCES IN LEE 2525

Table 5 lists the light and heavy elemental abundances derived in this study for two models for Lee 2525 as well as the results from Brown & Wallerstein (1992). As outlined in Section 3.1, the light elemental abundances were derived using *abfind* in MOOG, while heavy elemental abundances

¹ [Fe I, Fe II/H] refers to the Fe abundance derived from Fe I and Fe II lines respectively

Table 4. Stellar model parameters and resulting values of [Fe I/H] and [Fe II/H] for Arcturus and range of models for Lee 2525. Values at two different ξ values are also compared. The first model for Lee 2525 uses the Brown & Wallerstein (1992) parameters. The final model for Lee 2525 is the best fit determined in this study.

Star	Arcturus		Lee 2525					
T_{eff} (K)	4300		4225		4050		4225	
$\log g$	1.6		1.3		0.8		1.2	
[Fe/H] (dex)	−0.60		−0.82		−0.65		−0.70	
ξ (km s^{-1})	1.5		1.5		1.5		1.8	
[Fe I/H]	−0.61	± 0.12	−0.53	± 0.18	−0.64	± 0.17	−0.72	± 0.16
[Fe II/H]	−0.56	± 0.05	−0.71	± 0.05	−0.60	± 0.02	−0.74	± 0.08
ξ (km s^{-1})	2.0		2.0		2.0		2.0	
[Fe I/H]	−0.90	± 0.13	−0.86	± 0.18	−0.98	± 0.20	−0.84	± 0.18
[Fe II/H]	−0.69	± 0.10	−0.81	± 0.09	−0.72	± 0.06	−0.77	± 0.09

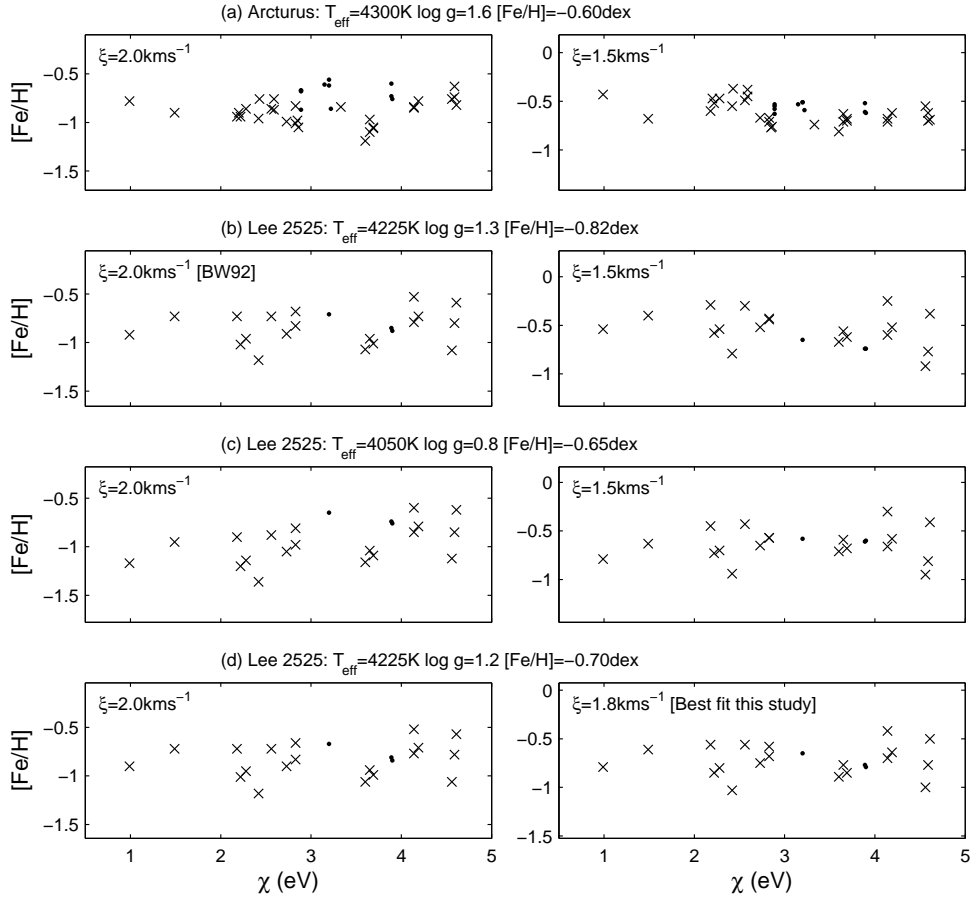


Figure 3. Comparison of [Fe/H] vs χ derived from Fe I (\times) and Fe II (\bullet) lines. (a) [Fe I/Fe II/H] derived for Arcturus using the measured Arcturus equivalent widths. (b) As for (a) but for the Brown & Wallerstein (1992) stellar model and the Lee 2525 measured equivalent widths. (c) As for (b), but for a high metallicity model and the Lee 2525 equivalent widths. (d) As for (b), but for the best fit stellar model determined for Lee 2525 in this study and the Lee 2525 equivalent widths. The figures in the lefthand column show the derived [Fe I/Fe II/H] values for the specified stellar atmosphere models at $\xi = 2.0 \text{ km s}^{-1}$. The figures in the righthand column are the same but for $\xi = 1.5 \text{ km s}^{-1}$ except for the best fit model in (d).

Table 5. The light and heavy elemental abundances derived in this study from two stellar models for Lee 2525 compared with the values derived in Brown & Wallerstein (1992). The uncertainty on the mean (σ) and number of lines used to derived the abundance (N) are included. The variation in abundances due to changes in stellar parameters corresponding to $\Delta T_{eff} = +100$ K, $\Delta \log g = +0.5$ and $\Delta \xi = +0.5$ km s⁻¹ are also shown.

T_{eff} (K) $\log g$ $[\text{Fe}/\text{H}]$ (dex) $\xi(kms^{-1})$	BW92			This Study							
	4225			4225		4225					
	1.3			1.3		1.2					
	-0.82			-0.82		-0.70					
	2.0			2.0		1.8					
Species	[X/H]	σ	N	[X/H]	σ	[X/H]	σ	N	ΔT_{eff} +100K	$\Delta[\text{X}/\text{H}]$ $\Delta \log g$ +0.5	$\Delta \xi$ +0.5kms $^{-1}$
Fe I	-0.83	0.16	22	-0.85	0.18	-0.72	0.16	19	0.01	0.11	-0.23
Fe II	-0.82	0.17	5	-0.81	0.09	-0.73	0.08	3	-0.12	0.32	-0.06
	[X/Fe]	σ	N	[X/Fe]	σ	[X/Fe]	σ	N	$\Delta[\text{X}/\text{Fe}]$		
O I	-	-	0	0.45	-	0.40	-	1	0.01	0.18	-0.01
Na I	-0.01	0.06	2	0.15	0.06	0.05	0.05	2	0.09	0.01	-0.07
Mg I	-	-	0	0.43	0.02	0.34	0.04	2	0.01	0.05	-0.06
Al I	0.51	0.23	2	0.32	0.02	0.21	0.03	2	0.08	0.02	-0.08
Si I	0.21	0.14	6	0.43	0.20	0.36	0.20	7	-0.07	0.14	-0.06
Ca I	-0.03	0.06	9	0.04	0.21	0.00	0.23	8	0.11	0.00	-0.24
Sc II	-0.04	0.06	2	0.06	0.07	0.05	0.08	2	-0.03	0.22	-0.13
Ti I	0.17	0.09	7	0.24	0.19	0.14	0.18	9	0.17	0.05	-0.09
Ti II	0.42	-	1	0.19	0.06	0.17	0.04	2	-0.05	0.23	-0.11
Zn I	0.14	0.03	2	0.04	0.15	0.05	0.16	2	-0.08	0.16	-0.24
Y I	0.58	-	1	0.60	0.25	0.51	0.28	2	0.25	0.09	0.01
Y II	0.41	0.47	2	0.44	-	0.54	-	1	0.07	0.20	-0.50
Zr I	-0.51	0.24	3	0.37	0.04	0.36	0.04	3	0.15	0.03	-0.12
Zr II	-	-	0	0.70	-	0.65	-	1	0.05	0.25	-0.03
Ba II	-0.15	0.21	3	-0.32	0.02	-0.21	0.01	2	0.06	0.27	-0.49
La II	0.10	0.40	2	0.34	0.01	0.31	0.03	3	0.04	0.24	-0.05
Nd II	-	-	0	0.40	-	0.41	-	1	0.11	0.31	0.05
Eu II	0.44	-	1	0.48	-	0.40	-	1	0.12	0.38	0.11
	[X/Y]	σ		[X/Y]	σ	[X/Y]	σ		$\Delta[\text{X}/\text{Y}]$		
<i>ls</i> /Fe	0.16	0.50		0.53	0.20	0.51	0.22		0.13	0.14	-0.16
<i>hs</i> /Fe	0.10	0.40		0.37	0.01	0.36	0.03		0.08	0.27	0.00
<i>hs</i> / <i>ls</i>	-0.06	0.64		-0.16	0.15	-0.16	0.18		-0.05	0.13	0.16

were derived using MOOG’s spectrum synthesis function, *synth*.

Given the similar nature of the stellar parameters for Lee 2525 derived in this study to those derived in Brown & Wallerstein (1992), elemental abundances using both models were calculated for a complete comparison. In Table 5 the abundances derived in Brown & Wallerstein (1992) are quoted in column 2 with associated uncertainties and the number of lines used. Column 5 lists the abundances derived in this study using the Brown & Wallerstein (1992) stellar model parameters, and column 7 lists the abundances derived using the best fit model determined in this study. Columns 10 to 12 list the changes in abundance with associated changes in T_{eff} , $\log g$ and ξ .

As described in Section 3.2 the placement of the continuum for the measurement of the equivalent widths introduced a key source of uncertainty for the abundances measured in this analysis. This is likely to be the main source of discrepancy between this analysis and the element abundances determined in Brown & Wallerstein (1992). While

the spectra in both studies was of similar resolution ($R \sim 20,000$) the SNR in this study was considerably lower. It must also be noted that Brown & Wallerstein (1992) used a mixture of solar and laboratory *log gf* values but only laboratory *log gf* values were used in this analysis. Also Brown & Wallerstein (1992) used the solar abundances reported in Anders & Grevesse (1989) while those of Lodders (2003) were used here.

4.1 Light elements: O to Zn

Comparing the abundances we derived using the Brown & Wallerstein (1992) parameters with the Brown & Wallerstein (1992) results, there is reasonable agreement (to within 1σ) for the majority of the light elements. The key differences were: Al I, which was less abundant in this study by 0.19 dex; Ti II, which was less abundant by 0.23 dex; Zn I, which was less abundant by 0.10 dex; and Sc II, which was over abundant by 0.10 dex.

Comparing the best fit model of this study with

Brown & Wallerstein (1992), similar comments can be made. In general the light elemental abundances agree within 1σ . Sc II and Zn I are also enhanced using this model compared to Brown & Wallerstein (1992), while Ti II is still significantly depleted. However, of the three sets of stellar atmosphere models, the best fit model derived in this study provided the best agreement between Ti I and Ti II abundances indicating a better choice of $\log g$, at least in terms of Ti.

The error analysis in Table 5 shows that the strong lines of Sc II and Zn I used in this study are highly sensitive to changes in ξ as is the case of strong lines. Also both Sc II and Ti II are sensitive to changes in gravity as is expected for ionised lines.

This study confirms the abundance correlations previously observed for this star in Brown & Wallerstein (1992), namely a correlation of Al and Na abundance with CN strength. Another key abundance anomaly is the Na-O anti-correlation observed in 47 Tuc (see Carretta et al. (2004) and references therein). An O abundance was not measured in Brown & Wallerstein (1992). However, it was obtained in this study using the forbidden O I line at 6300 Å. Lee 2525 is enhanced in O ($[O/Fe] = 0.40$ dex), while Na is not ($[Na/Fe] = 0.05 \pm 0.05$ dex). These values fall clearly within the anti-correlated trend of $[Na/Fe]$ to $[O/Fe]$ shown in Figure 5 of Carretta et al. (2004).

The abundances of Mg and Al are both enhanced in agreement with previous studies. There is no indication of an anti-correlation between Mg and Al (Carretta et al. 2004; Koch & McWilliam 2008). As 47 Tuc is a metal-rich globular cluster this anomaly is not expected (Gratton et al. 2004).

With regard to Ca, previous studies have shown enhancements in 47 Tuc stars (Carretta et al. 2004; Koch & McWilliam 2008). However, the analysis of this star found a Ca abundance of $[Ca/Fe] = 0.00$ dex, in agreement with the value determined in Brown & Wallerstein (1992) ($[Ca/Fe] = -0.03$ dex).

The Ti abundance is slightly enhanced ($\sim +0.15$ dex) in this study for both Ti I and Ti II. In Brown & Wallerstein (1992) Ti I was enhanced at this same level while Ti II was greatly enhanced ($\sim +0.42$ dex). This implies that there is a $\log g$ determination issue in their study due to the neutral and ionised species being out of equilibrium.

For a sample of five red giants, Alves-Brito et al. (2005) found the mean abundances for Ca to be $[Ca/Fe] = 0.0$ dex and Ti to be $[Ti/Fe] \sim 0.25$ dex. The Ca and Ti abundances derived in this study agree with Alves-Brito et al. (2005) within the uncertainties.

In Alves-Brito et al. (2005) a comparison of Ca abundances was made between Brown & Wallerstein (1992) and Carretta et al. (2004). The lack of enhancement in Ca in Brown & Wallerstein (1992) was noted. The stellar sample in Carretta et al. (2004) all had enhancements in Na and Ca, while the Alves-Brito et al. (2005) sample showed no enhancements in the mean abundances of both Na and Ca. While the correlation of Na with CN can be explained as leakage from the CNO cycle, a variation of Ca with Na or CN is not expected. Further investigation of Ca abundances is needed in order to clarify the reported abundances for this element in 47 Tuc.

Overall this analysis of Lee confirms previous abun-

dance anomalies within 47 Tuc giant branch stars with regards to CN, Na and O.

4.2 Heavy elements: Y to Eu

The comparison of the heavy elemental abundances show that the current analysis of Lee 2525 carried out using the Brown & Wallerstein (1992) stellar atmosphere model returns slightly higher abundances than the values found in the paper itself. Zr and La show enhancements relative to Brown & Wallerstein (1992), while Ba is depleted.

The best fit stellar model in this study also shows Zr and La are enhanced compared with the Brown & Wallerstein (1992) values. However, there is better agreement between the Y I values and the Y II abundance values. There is also a large uncertainty in the Brown & Wallerstein (1992) La abundance within which the value from this study resides. While Ba is depleted here with respect to Brown & Wallerstein (1992) the effect is not so great and the abundances agrees within the uncertainties. While the Eu abundance for both studies is based on only one line so no σ is available, the difference between the abundances is only 0.04dex. Given the high sensitivity of Ba II to $\log g$ and ξ it was not included here in the definition of the heavy s -process index, hs . As such for this study $ls = \langle Y \text{ I, Y II, Zr I, Zr II} \rangle$ and $hs = \langle La \text{ II, Nd II} \rangle$.

The Zr abundances are of particular interest as there is a significant difference between them and the Brown & Wallerstein (1992) results. Using the Brown & Wallerstein (1992) parameters an enhancement in Zr of $[Zr \text{ I/Fe}] = +0.37$ dex and $[Zr \text{ II/Fe}] = +0.70$ dex was determined in this study. The best fitting model returned values of $[Zr \text{ I/Fe}] = +0.36$ dex and $[Zr \text{ II/Fe}] = +0.65$ dex compared with $[Zr \text{ I/Fe}] = -0.51$ dex as determined in Brown & Wallerstein (1992). In order to investigate these differences further Figure 4 shows the observed spectrum for Arcturus and Lee 2525 in a key region containing three Zr I lines used in this study, two of which were used in Brown & Wallerstein (1992).

In Figure 4b Lee 2525 is overlaid with a synthetic spectrum generated using the Brown & Wallerstein (1992) model. The Zr abundance has been varied to show the spectrum when Zr is depleted ($[Zr/Fe] = -8.0$ dex), Zr abundance at the value calculated in Brown & Wallerstein (1992) ($[Zr/Fe] = -0.51$ dex), the Zr abundance expected from the model ($[Zr/Fe] = 0.0$ dex) and the best fit Zr abundance in this study for the line at 6134.57 Å ($[Zr/Fe] = +0.33$ dex). Similarly in Figure 4c, a synthesised spectrum of the best fit model in this study is overlaid on Lee 2525 with the same variations to Zr, except the best fit Zr abundance for 6134.57 Å is $[Zr/Fe] = +0.35$ dex. In both cases the Zr features are enhanced with respect to the model abundance confirming the expected result of enhancements in Y coinciding with enhancements in Zr.

With Zr now similar to Y, these heavy elemental abundances fall within the spread of values determined for the s -process elemental abundances obtained in Wylie et al. (2006) confirming an enhancement of s -process elements in 47 Tuc (see Table 1).

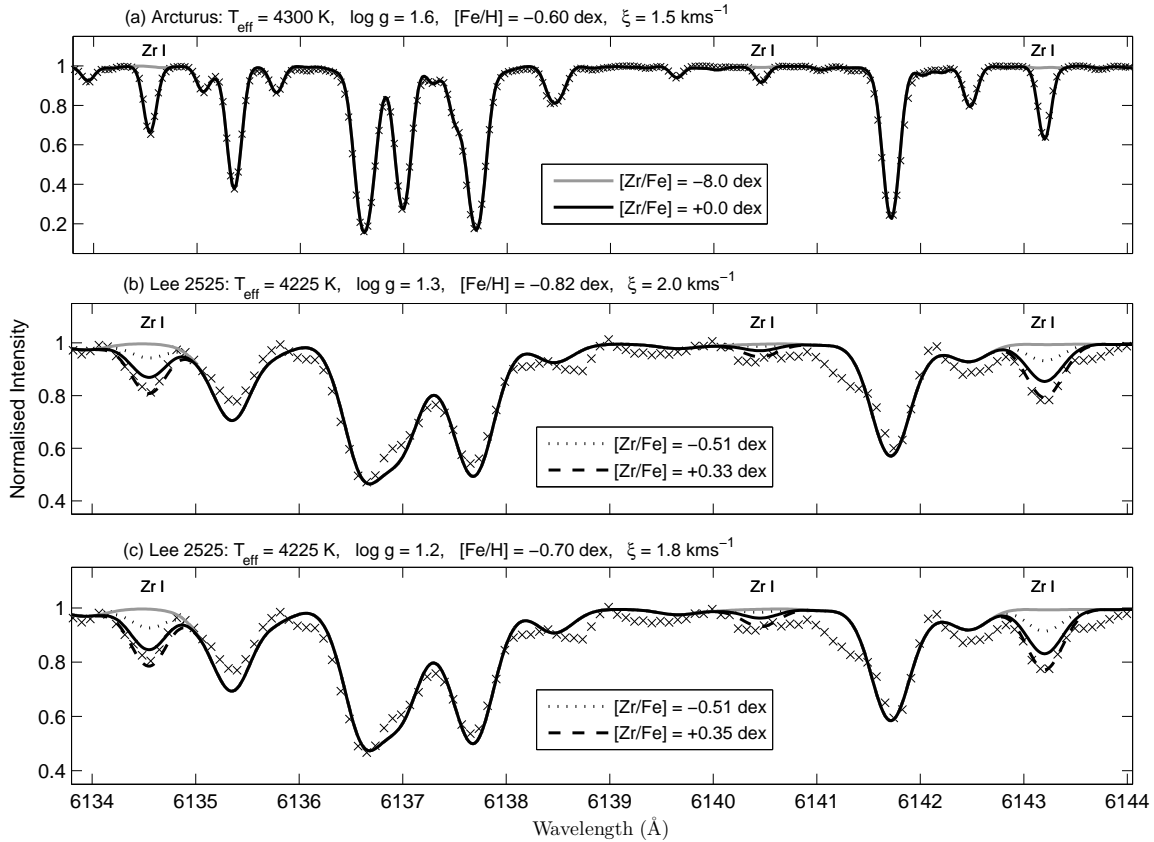


Figure 4. Wavelength region about 6140 Å showing the observed spectrum overlaid with spectra synthesised at different specified Zr abundances: (a) Arcturus spectrum where $[\text{Zr}/\text{Fe}] = +0.00$ dex provides the best fit to the Zr I lines; (b) Lee 2525 spectrum using the stellar model based on the stellar parameters specified in Brown & Wallerstein (1992). $[\text{Zr}/\text{Fe}] = -0.51$ dex is the best fit Zr abundance found in Brown & Wallerstein (1992). $[\text{Zr}/\text{Fe}] = +0.33$ dex is the best fit Zr abundance for this model in the current analysis; (c) Lee 2525 spectrum using the best fit stellar model parameters determined in this study. $[\text{Zr}/\text{Fe}] = +0.35$ dex is the best fit to the Zr abundance.

4.3 Lee 2525 abundances with respect to Arcturus

In light of this result for Lee 2525 the $[\text{Fe}/\text{H}]$ and $[\text{X}/\text{Fe}]$ relative to the Sun listed in Table 5 were recalculated relative to Arcturus and are listed in Table 6. This was carried out in order to remove any systematic errors within the analysis process by re-stating the abundances in Lee 2525 relative to a star of similar metallicity and atmospheric structure on which the process has been calibrated (Koch & McWilliam 2008).

While Arcturus and Lee 2525 have similar stellar parameters, Table 6 shows the clear differences in their chemical make up. For the most part, Lee 2525 is less abundant in the light elements than Arcturus and more abundant in the heavy elements. Si and Zn are both enhanced in Lee 2525 compared to Arcturus. However the derived uncertainties of Si and Zn in this study bring them in line with the other light element abundances.

Of the heavy elements, Ba II and Eu II show abundances similar to Arcturus. The strength of the Ba II lines and their sensitivity to ξ make the Ba II less reliable. As Eu is predominantly an r -process element, its abundance is a useful indication of how much pollution by supernovae the gas clouds underwent prior to the formation of stars. The

similar value between Lee 2525 and Arcturus could imply some similar degree of exposure. The similarity in Eu abundances between globular cluster stars and field stars has been noted previously (James et al. 2004).

The comparison between the Lee 2525 and Arcturus abundance results is a natural consequence of undertaking a differential analysis with a standard star. However, as Lee 2525 is a globular cluster star and Arcturus is field star, the comparison being made is really between two distinct stellar environments which is beyond the scope of this paper. The key adjustments due to differencing Lee 2525 with Arcturus is a reduction in the scatter of the s -process element abundances. For Zr and Y there is better agreement between their neutral and ionised abundances, and better agreement between these two light s -process peak elements overall. The abundances of the heavy s -process elements (La and Nd) are also brought in line. These effects are reflected in the $[\text{hs}/\text{Fe}]$ and $[\text{ls}/\text{Fe}]$ ratios although the $[\text{hs}/\text{ls}]$ ratio is only adjusted by 0.02 dex. These improvements imply the reduction of systematic errors in the results due to the analysis process. In the case of a larger set of stars within a globular cluster a similar differential analysis would be useful to reduce systematic errors within a study and thereby to produce more consistent results.

Table 6. [Fe/H], [X/Fe] and *s*-process abundance ratios for Arcturus, and [Fe/H], [X/Fe] and *s*-process abundance ratios calculated relative to Arcturus for the Brown & Wallerstein (1992) and best fit Lee 2525 stellar models, where $[X/Y]_{Arc} = [X/Y]_{*} - [X/Y]_{Arcturus}$. The results from Brown & Wallerstein (1992) are also re-calculated relative to Arcturus for comparison.

X	Arcturus [X/H]	This study		
		BW92 [X/H] _{Arc}	BW [X/H] _{Arc}	Best Fit [X/H] _{Arc}
Fe I	-0.61	-0.22	-0.24	-0.11
Fe II	-0.56	-0.26	-0.22	-0.17
<hr/>				
X	Arcturus [X/Fe]	BW92 [X/Fe] _{Arc}	BW [X/Fe] _{Arc}	Best Fit [X/Fe] _{Arc}
O I	0.57	-	-0.12	-0.17
Na I	0.15	-0.16	0.01	-0.10
Mg I	0.34	-	0.08	-0.01
Al I	0.25	0.26	0.06	-0.04
Si I	0.20	0.01	0.23	0.16
Ca I	0.19	-0.22	-0.15	-0.19
Sc I	0.24	-0.28	-0.18	-0.20
Ti I	0.35	-0.18	-0.11	-0.21
Ti II	0.33	0.09	-0.14	-0.16
Zn I	-0.04	0.18	0.07	0.09
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Y I	0.07	0.51	0.53	0.44
Y II	0.12	0.29	0.32	0.42
Zr I	0.01	-0.52	0.36	0.35
Zr II	0.12	-	0.58	0.53
Ba II	-0.19	0.04	-0.13	-0.02
La II	0.04	0.06	0.30	0.27
Nd II	0.10	-	0.31	0.32
Eu II	0.36	0.08	0.12	0.04
<hr/>				
	[X/Y]	[X/Y] _{Arc}	[X/Y] _{Arc}	[X/Y] _{Arc}
<i>ls</i> /Fe	0.08	0.09	0.45	0.44
<i>hs</i> /Fe	0.07	0.06	0.30	0.29
<i>hs</i> / <i>ls</i>	-0.01	-0.03	-0.14	-0.14

4.4 The *hs* to *ls* ratio in 47 Tuc giant stars

The *hs* and *ls* indices derived for Lee 2525 in this study were compared with Brown & Wallerstein (1992) and Wylie et al. (2006). Figure 5 shows the abundance ratio of the heavy *s*-process to light *s*-process elements ($[hs/ls]$) for Lee 2525 as well as for the other studies.

The *ls* indices for the Brown & Wallerstein (1992) stars were re-calculated to use only the Y I and Y II abundances in light of the above analysis of Zr. Considering the sample as a whole there appears to be no trend between the $[hs/ls]$ ratio and [Fe/H] in Figure 5. Given these stars all exist in the same cluster and therefore have the same metallicity within some variance, if there was a spread in $[hs/ls]$ values greater than the systematic spread on the [Fe/H] values, it would indicate that *s*-process elements were being produced in these stars.

Observational and theoretical studies have shown that for AGB stars undergoing third dredge up the $[hs/ls]$ ratio generally increases with decreasing metallicity, although the theoretical relations are naturally more complex (Busso et al. 2001). As the seed nuclei become fewer there is greater enhancement in the heavy *s*-process peak compared with the light *s*-process peak. As no such trend exists in this sample of 47 Tuc stars, it implies that the *s*-process

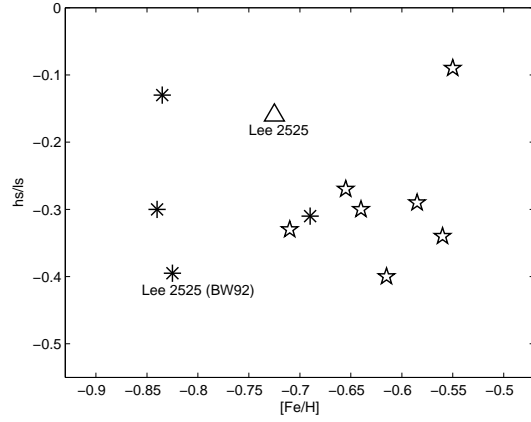


Figure 5. The ratio of the heavy to light *s*-process element abundance ($[hs/ls]$) for each star against [Fe/H]. (★) Wylie et al. (2006); (*) Brown & Wallerstein (1992) using $ls = \langle Y\ I, Y\ II \rangle$; and (△) Lee 2525, this study.

abundances observed here are primordial and are not being produced internally in these stars.

5 CONCLUSION

Studies to date of *s*-process element abundances in 47 Tuc stars have concluded that the observed *s*-process element abundances are due to the primordial chemical composition of the cluster or some pollution event early in the cluster's history. While within each study there is agreement as to the magnitude of the *s*-process element abundances, the abundances differ between the studies. The analysis of Lee 2525 carried out here resolves a discrepancy between Brown & Wallerstein (1992) and Wylie et al. (2006) as to the magnitude of the Zr abundance in this star. The current study found Lee 2525 to be enhanced in Zr at $[Zr/Fe] = +0.51$ dex which is in agreement with the enhancement found for Y of $[Y/Fe] = +0.53$ dex, another light *s*-process element. This is in line with *s*-process element enhancements found in 47 Tuc giant branch stars in Wylie et al. (2006). The Na-CN correlation reported in Brown & Wallerstein (1992) for Lee 2525 was also found here, as well as an Na-O anti-correlation in line with other studies of light elements in 47 Tuc stars (Carretta et al. 2004). These results support the premise that the abundance anomalies observed in 47 Tuc have a primordial or pollution-based origin.

While this study has resolved a discrepancy between two key papers the overall *s*-process element abundance distribution within 47 Tuc is still not clear. It is necessary to expand the sample of 47 Tuc stars analysed for their *s*-process element abundances in order to consolidate the results found here with those from other studies. This analysis was carried out differentially with respect to Arcturus in an effort to reduce systematic errors by calibrating the analysis process to a standard star of similar stellar parameters. This provides a solid framework for further study within this area.

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